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A review of different methods to enhance the productivity of the multi-effect solar still

T. Rajaseenivasan [a], K. Kalidasa Murugavel [b,*], T. Elango [c], R. Samuel Hansen [d]

[a] Department of Mechanical Engineering, Fatima Michael College of Engineering and Technology, Madurai-625020, Tamil Nadu, India
[b] Centre for Energy Studies, National Engineering College, K.R. Nagar, Kovilpatti-628503 Tamil Nadu, India
[c] Department of Mechanical Engineering, Udaya School of Engineering, Vellamodi-629204, K.K. District, Tamil Nadu, India
[d] Department of Mechanical Engineering, Infant Jesus College of Engineering, Keela Vallanadu-628851, Tamil Nadu, India

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ABSTRACT

In a simple horizontal or inclined basin type solar still, the basin receive solar radiation through the transparent cover, heats the water to evaporate, hot saturated air rises, vapour condenses at the cool lower surface of the glass cover, slides down and is collected using a drain. In a single effect still, the latent heat of condensation is exhausted as waste. In multi effect still, the heat of condensation of the previous effect is utilized in the next effect to heat the water. This article reviews the different methods tried by different researches to improve the productivity of multi effect solar still.
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* Corresponding author. Tel.: +919677928940; fax: +914632232749.
E-mail addresses: kali_vel@rediffmail.com, hodces@nec.edu.in (K. K. Murugavel).

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1. Introduction

Water is essential for all life forms on earth—plants, animals and human etc. For fresh water requirements humanity is dependent on rivers, ponds, lakes, and underground water reservoirs. The available fresh water in the earth is fixed. But the demand of fresh water is increases, due to population growth and rapid industrialization. Industrial wastes and sewage discharges are mostly mixed in the rivers, so the available fresh water is reduced. The provision of freshwater is becoming a gradually more important issue in many areas of the world. Ocean is the only available source for large amount of water. But the ocean water contains high salinity, so it needs to desaline the water.

Desalination is one of humankind's most primitive forms of water treatment, and it is still a popular treatment solution throughout the world today. In nature, solar desalination produces rain when solar radiation is absorbed by the sea and causes water to evaporate. The evaporated water rises above the earth surface and is moved by the wind. Once this vapour cools down to its dew point temperature, condensation occurs, and the freshwater comes down as rain. This basic process is responsible for the hydrologic cycle. This same principle is used in all man-made distillation systems using alternative sources of heating and cooling.

Desalination methods use large amount of energy (fossil fuels) to remove a portion of pure water from a salt-water source. The fossil fuels create pollution on environment and the availability of fossil fuel is limited. A solar still is a device, which is widely used in solar desalination process to produce potable water from brackish and saline water by using solar energy. Even through solar still is a very simple device, easy to fabricate and require only less maintenance, it is economical and not familiarly used because of its lower productivity [1,2].

Many solar distillation systems were developed over the years using the above principle for water purification in many parts of the world. Many researchers analyzed the works carried out on the solar still and reviewed. Malik et al. [3] have reviewed the work on passive solar distillation. Tiwari et al. [4] have carried out a study on the present status of research work on both passive and active solar distillation systems. Tiwari recommended that double slope passive solar stills can be economical to provide potable water for rural area. Murugavel et al. [5] studied about increasing the effectiveness of single basin solar still by using passive methods. Murugavel et al. concluded as providing of energy storing materials, wick materials, reducing water depth in basin increases the productivity of still. Sampathkumar et al. [6] made a detailed study on active solar distillation. They also discussed about theoretical analysis and modelling for active stills. Aayush and Varun [7] also reviewed about solar stills. Velmurugan and Srithar [8] studied about the various factors affecting the productivity of the solar stills. Kabeel and El-Agouz [9] reviewed the developments in solar still. There is no particular review available on multi effect solar still works, especially investigating the effect of additional basin, multi effect wick still, multi effect diffusion still and multi stage still. Therefore, this work is fully focused on the multi effect solar still works by different researches.

2. Different types of still

2.1. Basin still

In basin type solar still, impure water is taken in a well insulated air tight basin covered with transparent plastic/glass cover. When the cover is exposed sun, radiation energy is transmitted through transparent cover, falls on the basin, absorbed by basin absorber plate, converted into heat and transferred to water. Water gets heated up, transfer heat to air inside the still and the air become unsaturated. The water evaporates and makes the air inside still saturated. This air subjected circulatory motion due to the temperature difference between water surface and cover lower surface. When high temperature air touches the cover, become cool and the water present in the air condenses at the lower surface of the cover. This condensed water slides down and collected using a drain [3]. A schematic diagram of simple basin type solar still (single effect) is shown in Fig. 1.

2.2. Wick still

Wick still mostly come under inclined type still. In a wick still, the feed water flows slowly through a porous, radiation-absorbing pad (the wick). Two advantages are claimed over basin stills. First, the wick still can be tilted so that the feed water presents a better angle to the sun. It reduces reflection and presents a large effective area. Second, less feed water is in the still at any time and so the water is heated more quickly and to a higher temperature. The main disadvantage in this still is while cloud passing or after sunset, it does not produce distillate. However, in the case of basin still the productivity continuous for some time due to heat stored in the basin water. A schematic diagram of multi wick type solar still (single effect) is shown in Fig. 2.

2.3. Diffusion still

In the simple diffusion desalination process a hot and a cold surface are placed parallel to each other and separated by a small distance. A diluent gas such as air fills the gap between the two surfaces. The gap thickness is selected to be small in order to suppress heat transfer by convection between the two surfaces. Solar radiation transmits through the glass cover and is absorbed

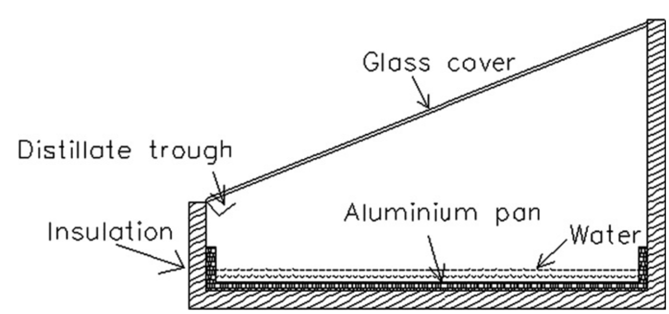

Fig. 1. Schematic diagram of a simple basin type solar still.

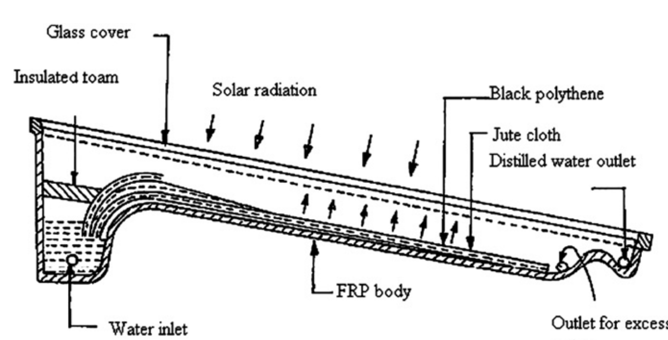

Fig. 2. Schematic diagram of a wick type solar still.

on the front surface of the partition. When feed water is allowed to flow over the hot surface, water vapour diffuses across the gap where it is condensed on the cold surface. This process is called diffusion desalination. A schematic diagram of a single effect diffusion type solar still is shown in Fig. 3.

3. Multi basin still

The low efficiency of most conventional single-effect stills is due to poor dissipation of the latent heat of the condensing vapour at the condensing surface. In multi-basin still the latent heat of vaporization released by the glass surface of lower basin is used to heat the upper basin water rather than being wasted to the surroundings. Therefore it increases the evaporation and condensation rate in the still. The additional basin is made up of transparent material (usually glass) to allow the radiation to lower basin. In additional basin clear brackish water only can be used.

3.1. Multi basin—Passive

In this type of still, productivity is increased by increasing the number of effects in the still. Al Mahdi [10] conducted an analysis to predict the effect of number of basins on the daily productivity of the still. The results show that, the double-basin still gives the highest productivity peak. However, the triple and quadruple-basin stills continue to produce appreciable amounts of distillate during the night, thereby leading to higher daily productivities. But, providing a basin beyond this does not have significant effect on productivity. Sodha et al. [11] presented an analysis of a double-basin solar still and examined its performance for various systems and climatic conditions. The result shows double basin still gives 36% higher than that of a single basin. In addition, it shows productivity increases rapidly with increasing insulation thickness up to 4 cm and then it increases rather slowly.

Experimental investigation on the effect of enhanced evaporation area results showed a gain of around 19.6% in the yield when the evaporation area was quadrupled, and an asymptotic (infinite area) gain of around 30.2%. The analysis also suggested that stills with an enlarged evaporation area could utilize cheap thermal energy from sources at relatively low temperatures such as solar ponds [12].

The main factor affects the production rate of the still is condensation surface (glass) temperature. Reducing the glass temperature leads to increase the productivity. The process of flowing water above the glass cover shows a good effect on the upper basin distillate output and efficiency of the system (Fig. 4) [13]. Lower glass surface temperature increases the circulation of air inside the still which enhances convective and evaporative heat transfer between basin water and glass, also cooler glass lower surface increases condensation [14].

The glass cover temperature is reduced and productivity is increased by continuous flow [15] or intermittent flow [16] of raw cooling water on the cover [17]. The cooling water gains latent heat from condensing water and regenerates it in the basin. A/K Abu-Hijleh et al. [18] result shows flowing of water increases the production rate by 20%. Yousef and Abu-Arabi [19] results also show that, the use of the film-cooling increases the still efficiency up to 20%. To utilize the flowing water heat energy, an additional glass is provided above the glass surface. It produces an additional effect in still and leads to increase the productivity. Regenerative still with lower depth of water gives higher productivity [20].

Dutt et al. [21] investigated the effect of adding dye in the double basin still. Result shows that an addition of dye increases the system efficiency by 10% and that the evaporative heat-transfer coefficients are strong functions of temperature, whereas the convective and radiative heat-transfer coefficients vary little with temperature.

The performance of the multi basin still is strong dependence function of the water mass uses in basin. Reducing the water mass in basin increases the distillate output. Tiwari et al. [22] investigated the performance of the double basin still and concluded that the total production of the still strongly depends on the water depth in the lower basin. For less water depth, the yield was enhanced, but the distillation ceases during off-sunshine hours. For greater water depths, the distillate output is reduced, but distillation continues even during off-sunshine hours.

Yeh [23] experimentally investigated the upward-type, double-effect solar distillers (Fig. 5). The still was placed 10° inclinations to horizontal surface. He found that using of upward-type, double-effect solar distillers gave more efficient than downward-type unit. Investigation on performance of the single, double and triple basin pyramid still was made by Hamdan et al. [24]. Result shows triple effect solar still is of maximum daily efficiency followed by the double effect still, with the single effect still of the least efficiency.

Cappelletti [25] designed and investigated the double basin solar still as shown in Fig. 6. The upper basin of the still was designed as 'V' shape. The condensed water of the lower basin was collected in middle of the lower basin. The result shows efficiency of the still is about 16%, it was due to low temperature of the water in basin (around 50 °C). Al-Hinai et al. [26] presented the parametric investigation of a double effect solar still and compared with a single-effect solar still. The shallow water basin with asphalt coating of the solar still were used in the study was

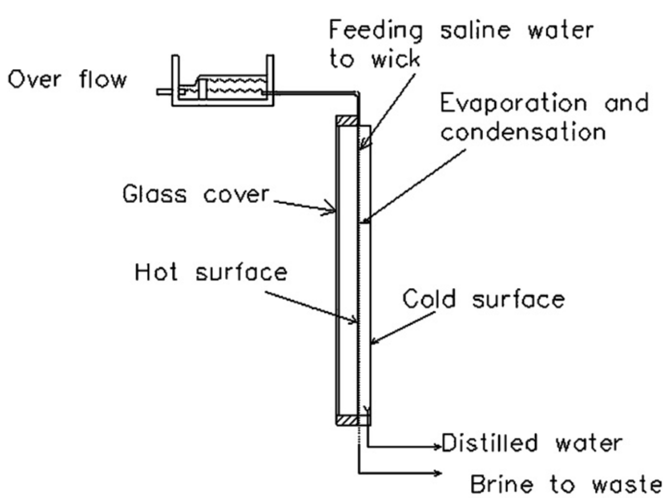

Fig. 3. Schematic diagram of a single effect diffusion type solar still.

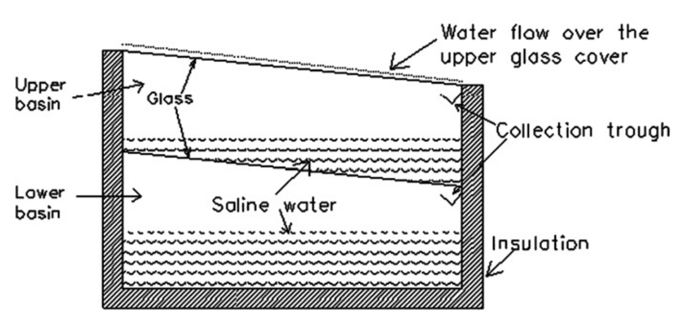

Fig. 4. Schematic of double basin solar still with water flowing over upper glass cover [13].

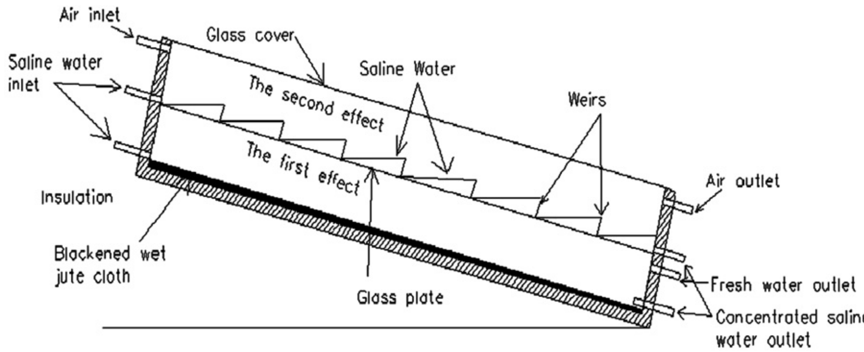

Fig. 5. Upward-type, double-effect solar distillers [23].

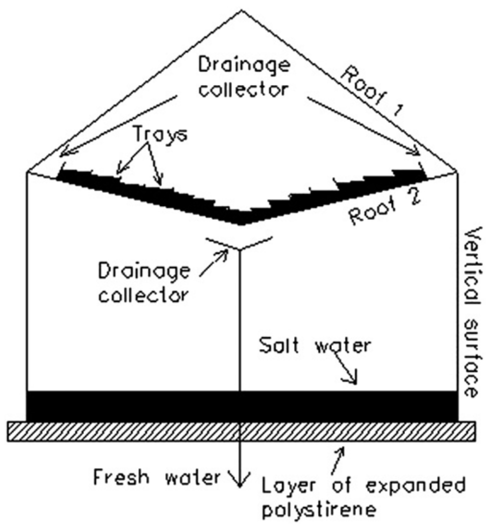

Fig. 6. Double basin solar still [25].

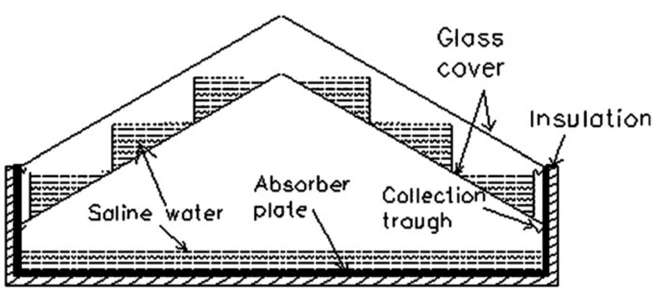

Fig. 7. Schematic diagram of double basin double slope solar still [31].

produced an average annual solar still yield of 4.15 kg/m^2/day and 6 kg/m^2/day for single and double effect solar stills, respectively. Fukui et al. [27] theoretically studied the multi effect solar still and concluded as using of multi effect still increases the productivity. Al-Karaghoulia and Alnaserb [28,29] experimentally studied the performances of single and double basin solar-stills. Result shows production rate increases with the double basin still; also insulation has significant effect on the productivity, especially for the double-basin type.

Kumar et al. [30] inferred the effect of additional basin in double slope still. The result shows that, (i) the water and glass temperature decreases with increase of the heat capacity of the water mass in the basin of the still, hence the yield also decreases. (ii) The daily yield increases with the decrease of heat capacity of the water mass in the upper basin due to better utilization of the latent heat of vaporization. (iii) The daily yield from the lower basin is higher than the upper basin. (iv) The efficiency of the double basin solar still is significantly higher than the single basin solar still. (v) There is a significant variation in efficiency with increasing the lower basin water temperature from 30 °C to 38 °C. A double basin double slope still was fabricated and experimentally analyzed with different basin conditions by Rajaseenivasan et al. [31] (Fig. 7). The results were compared with the conventional single basin double slope still. The upper basin of the double basin still was split into three compartments (each side) to spread the water mass evenly through the entire area of the upper basin. The tests were conducted with different depth of water in the basin, mild steel pieces as energy storing material, black cotton cloth, jute cloth, and waste cotton pieces as wick materials and small clay pot as porous material. The productivity of the double basin still with energy storing materials in lower basin was 169.2% higher than the conventional still.

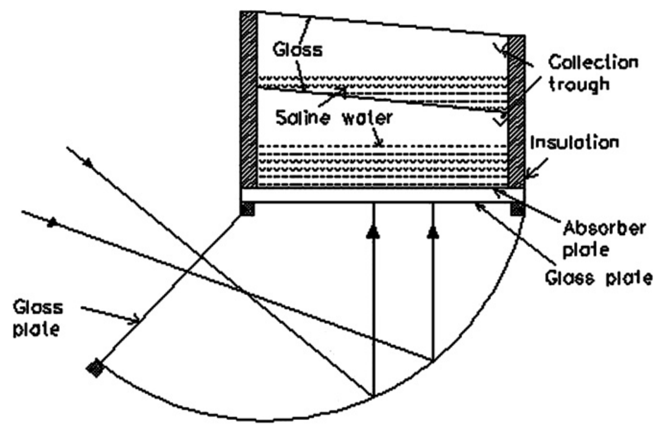

Fig. 8. Schematic view of an inverted absorber double basin solar still [33].

3.2. Multi basin—Inverted

In this type of still, the water temperature increases by inverting the absorber to reduce the bottom heat loss [32]. Inverted absorber solar still produces double than conventional solar still. Sangeeta and Tiwari [33] inferred the effect of water depth on the double basin inverted still (Fig. 8). They concluded as the total yield of the system maximum for the least depth in lower basin. Sangeeta et al. [34] investigated the parametric study on inverted double effect solar still. Result shows increasing the initial water temperature from 22 °C to 35 °C, the yield of an inverted absorber double-basin solar still increase by about 10%. The yield of an inverted absorber double basin solar still increases by about 99% as the absorptivity of the absorber increases from 0.55 to 0.95. Inverted triple effect still produces more distillate

than the conventional triple effect still. Also it shows that the daily yield significantly increases as the number of effects increases from the first effect to the third effect [35]. In inverted solar still while the number of basins is increased beyond seven, there is only a marginal increase in the yield. Also the yield from a seven-effect inverted absorber solar still was about 4.2 times that from an inverted absorber single-basin solar still [36].

3.3. Multi basin—Active

The temperature difference between water in the basin and condensing glass cover has a direct effect in the productivity of the still. The increased water temperature increase the temperature difference between the evaporating and condensing surfaces. To achieve better evaporation and condensation rate, the temperature of basin water could be elevated by supplying thermal energy from some external sources. The water temperature of the still is increased by supplying additional thermal energy through solar collectors to the basin. The additional energy is mostly supplied to the lower basin of the still since it receives less radiation than upper basin, due to decreases in transmitivity by additional basin.

3.3.1. Multi basin—Waste hot water flow

Gupta et al. [37] analyzed a double basin solar still with incorporating flowing of waste hot water in night at the lower basin. It shows yield of the still increases with the inlet temperature of waste hot water and increasing the flow of waste hot water. The productivity decreases with in water mass in lower basin.

3.3.2. Multi basin—Flat plate collector

Tiwari [38] analyzed the effect of double basin still with water flowing over the glass cover and using flat plate collector to supply hot water in lower basin. It was found that using of flat plate collector gives 50% higher yield than the normal double basin still. Also higher yield observed when the collector was disconnected from the still during off-sunshine hours to avoid heat losses through the collector. Yadav [39] and Yadav and Jha [40] analyzed the double basin still with and without flat plate collector (thermosiphon and forced circulation mode) (Fig. 9). They concluded as performance of the system with forced circulation was slightly better than thermosiphon mode. It is also suggested to use thermosiphon mode in the places where electricity is not available.

Tiwari and Lawrence [41] conducted a thermal analysis for double effect still with flat plate collector. In this study, upper basin water is flowing instead of stagnant of huge mass of water in the basin. It results in increased evaporation rate as well as increases the radiation entering into the lower basin. The daily yield increases with decrease of flow rate of water in upper basin. Kumar and Tiwari [42] presented the performance of daily yield

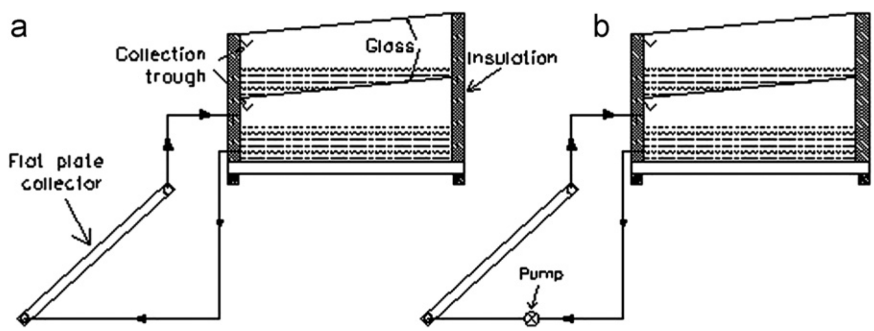

Fig. 9. Schematic of a (a) solar still coupled to a collector in the thermosiphon mode and (b) Solar still coupled to a collector in the forced circulation mode [39].

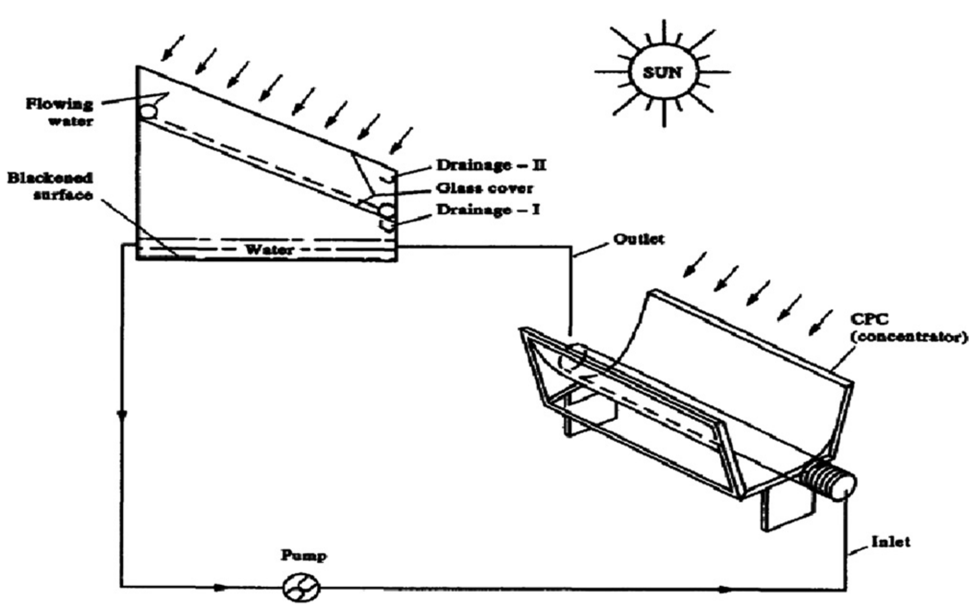

Fig. 10. Cross-sectional view of double effect active distillation system [45].

for an active double effect distillation system with water flow. A higher yield 3.34 kg/m^2/h from the lower basin was obtained at the noon, due to the high water temperature of 95 °C at that time. With the decreases in water masses, the operating water temperature in the lower basin is improved resulting in increased yield and efficiency. The daily yield increases with an increase of collector area, because the thermal energy in the basin increases as the collector area increases.

Integrating a double basin still with the flat plate collector and flow the water over the upper basin glass cover produces maximum distillate output [43]. The solar still operating in the double effect mode without collector does not enhance the daily output significantly because of the difficulties in maintaining reasonably low and uniform flow rates over the glass cover (10 ml/min). Al Baharna et al. [44] presented a performance analysis on triple basin still integrated with the solar collector. It was found that daily productivity of the still increases from 10.64 kg/day to 24.48 kg/day when the area ratio of the heater to the still was unity. Although the daily productivity of the still increases with increasing the area of the water heater.

3.3.3. Multi basin—Parabolic collector

Bhagwan and Tiwari [45] presented an analysis of a double effect, solar distillation unit coupled compound parabolic concentration (CPC) collector under forced circulation mode (Fig. 10).The authors suggested that, (i) the temperature of the water in the lower basin is increased in comparison with single effect distillation due to the reduced upward heat losses. (ii) The hourly output in the lower basin is reduced due to the reduced temperature difference between the water and glass temperatures. However, the overall output is increased due to reutilization of the latent heat of evaporation in the second effect. (iii) The hourly yield from the lower basin increases with increase of flow velocity of water in upper basin due to the decrease in the lower glass temperature. (iv) The evaporative heat transfer coefficient is a strong function of the operating temperature range. The convective and radiative heat transfer coefficient does not vary significantly.

Garcia and Gomez [46] experimentally studied the multi effect distillation system coupled to a parabolic through collector (PTC) for sea water desalination and suggested the following, (i) the annual energy production is about 23% greater for a north–south collector than for an east west one. (ii) The optimum axis height for a single collector is 29° and it is 12% higher production than a horizontal collector for an inlet/outlet thermal oil temperature of 225 °C to 300 °C. (iii) The maximum yearly average of the daily operation time is only about 12 h/day in coastal areas in southern Spain.

3.3.4. Multi basin—Heat exchanger

Yadav [47] presented a performance analysis on double basin still coupled to a heat exchanger. It is observed that the efficiency of the proposed system is considerably less than the double basin still without heat exchanger. In addition, the performance of the system is strong function of the heat exchanger parameters; the efficiency of the system also increases considerably with the increased mass flow rate, in the region 0– 20 kg/h. The efficiency of the double basin still with heat exchanger can be increased by increasing the length of pipe in the region of 0– 5 m. A double basin still with heat exchanger system used for study is shown in Fig. 11 [48]. Tiwari and Sharma [49] studied the double effect solar distillation under active mode of operation using heat exchanger. The study shows that, there is an increase of about 30% in the active solar still due to water flow through the upper basin and there is a marginal increase in efficiency with increase in the length of the heat exchanger.

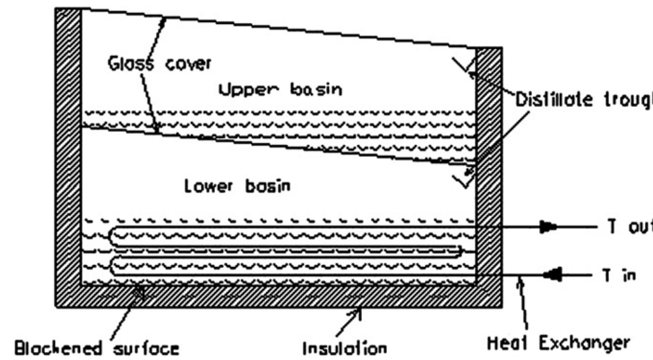

Fig. 11. Schematic of the double-basin solar still integrated with a heat exchanger [48].

4. Additional condenser

In a simple conventional still, the bottom surface of the glass cover is only area available for condensation and the temperature difference available across glass thickness is very small. Hence, the condensation rate is less. This makes the still inefficient. The condensation rate can be increased by providing an additional area for condensation. Due to providing additional area, heat capacity of the evaporation area increases and the latent heat of condensation used by water in upper basin of condenser area.

Fath [50] inferred the performance of a two effect solar distillation unit. In this, the evaporated vapour from the first effect is allowed to be purged to the second effect (Fig. 12). The second effect cover has a finned outer surface to maintain the cover at or near ambient temperature, and a reflective inner surface to minimize radiation losses. The daily productivity was observed as 10.7 kg/m^2/day, for the proposed unit under the climatic conditions of the city of Dhahran, Saudi Arabia.

A passive solar still with separate condenser was modelled and performance was evaluated by Madhlopa and Johnstone [51]. The system has one basin (basin 1) in the evaporation chamber and two other basins (2 and 3) in the condenser chamber, with a glass cover over the evaporator basin and an opaque condensing cover over basin 3 (Fig. 13). The top part of the condensing cover was shielded from solar radiation to keep the cover relatively cool. Water vapour from the first effect condenses under the glass cover while the remainder of it flows into the condenser, by purging and diffusion, and condenses under the liner of basin 2. Results show that, the distillate productivity of the still was 62% higher than that of the conventional type.

5. Multi stage and evacuated solar still

Water desalination with heat recovery is a good solution for a better output. The multistage, stacked tray solar still produces more distillate than that produced by the ordinary diffusion type solar still [52,53]. The influence of the wind on the performance of the multi effect-stacked tray solar still was found to be very important, and the output was reduced very much for high wind velocities because the still was not tight enough. The multistage evacuated solar still was proven to be of a better output rate than all the previous systems.

Jurban et al. [52] numerically investigated the multi stage evacuated solar still. The solar still consists of three insulated stages placed on top of each other. There was perfect sealing between the different stages such that the water vapour which evaporated during the boiling can pass only through the small orifice that connects two stages. The still can produce up to

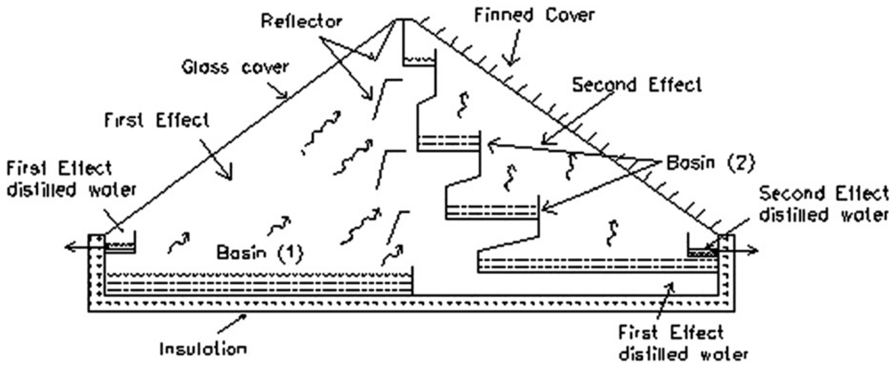

Fig. 12. Schematic diagram of solar still with separate condenser [50].

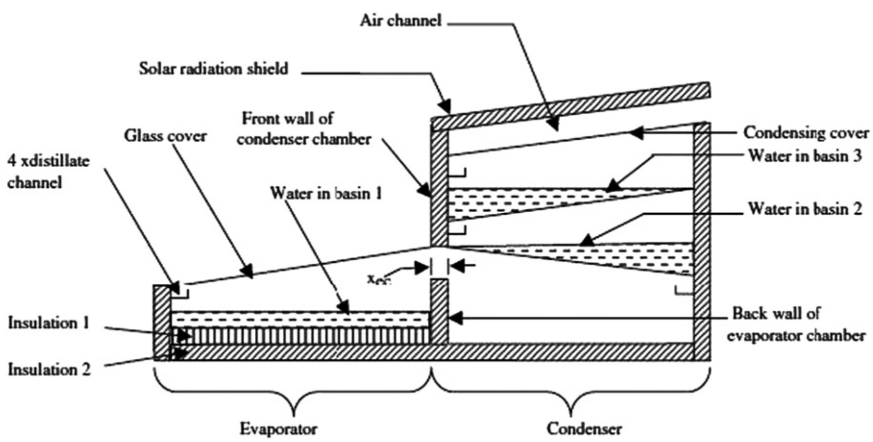

Fig. 13. Solar still with inbuilt condenser [51].

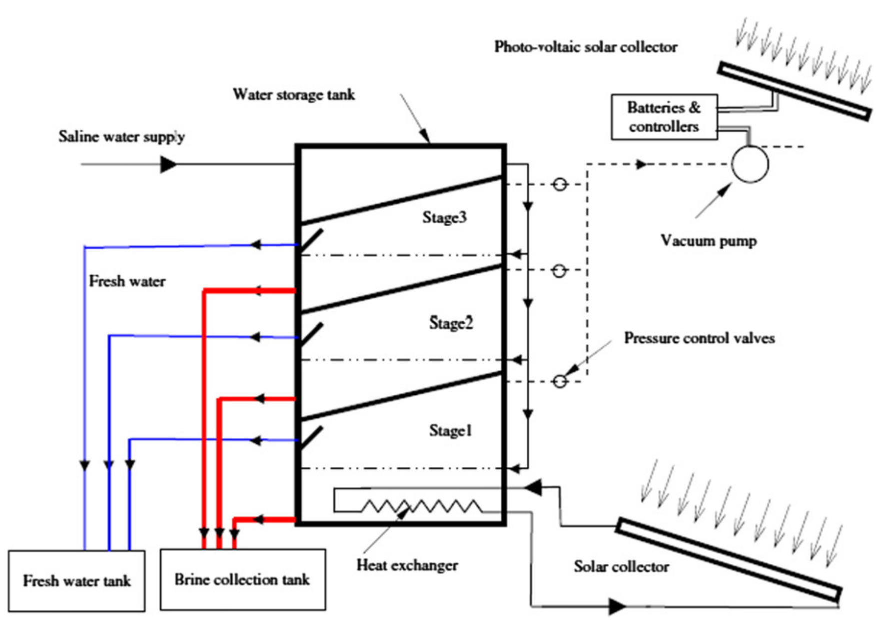

Fig. 14. Schematic diagram of the evacuated multistage solar still [60].

9 kg/m^2/day with a distillation efficiency of 87%. Uda et al. [54] reported the development of an evacuated solar still.

Hassan et al. [55] investigated the multi effect solar still for agriculture purpose in hot climate. They used a five stage solar still as a simple shelter for plants in hot arid climates of the Middle East. Goff et al. [56] developed a rugged design of high efficiency Multi-Stage Solar Still. They observed that the unit produces more than 20 l/m^2/day, under the same conditions of sunshine single basin still produces 2.5 l/m^2/day to 3 l/m^2/day.

Jose and Norberto [57] inferred the indirectly heated multi stage solar still. In this system heat was supplied to the lowermost tray, containing seawater like all the rest, and a diffusion

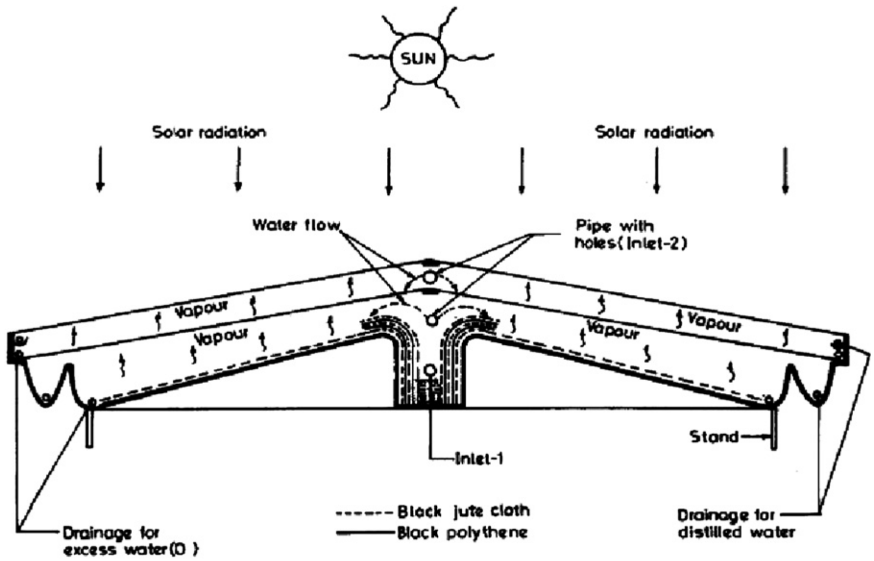

Fig. 15. Schematic of double effect, wick type solar still [63].

distillation occurs. Evaporation from the hottest tray causes condensation onto the upper, colder one, thus producing distilled water and a flow of heat upwards. Energy supplied from 32 flat plate collectors with an effective collecting area of 1.59 m^2 each. It produces minimum of 40 l/day and maximum of 80 l/day depend upon the month. A techno-economic model was developed for a multi-stage stacked tray solar still using a flat plate collector [58]. A three-stage desalination system with air evacuation, coupled with a solar collector and photovoltaic cells with a total distillation unit of dimensions 9 m in the length, 3.2 m in width and 2.3 m in height, was built and tested in the Gaza Strip by Abu-Jabal et al. [59].

Ahmed et al. [60] designed, fabricated and tested the multi-stage evacuated solar still system that consists of three stages stacked on the top of each other, and are carefully insulated from the outside environment using rock–wood and aluminium foil layers to prevent any losses to the ambient environment. The three stages are mounted on top of each other and a good sealing is maintained between the stages to prevent any vapour leakage through the contact surfaces. A thick insulation is also used to reduce heat losses of the still to the ambient. A solar collector is used to supply heat to the system through the lower stage, which is maintained at a pressure lower than atmospheric by means of a heat exchanger. A solar operated vacuum pump is used to evacuate the non condensable gases from the stages. Fig. 14 shows a schematic diagram of the multistage evacuated solar still.

Saline water is fed into each stage from the tank located at the top of the third stage. Vapour generated in the lower stage condenses on the bottom surface of the intermediate stage, giving its heat to the saline water in the intermediate stage. Vapour generated in the intermediate stage condenses at the bottom surface of the upper stage giving its heat to the saline water in the upper stage. The feed water is preheated by the heat given to it by condensation of the vapour generated at the upper stage, which condenses at the bottom of the feed water tank. Pressure inside each one of the three stages is kept lower than the previous stage. Vacuum is generated using a solar operated vacuum pump. A set of valves is used to control the vacuum inside the different stages. The results show that, the maximum production of the solar still was found in the first stage and is 6 kg/m^2/day, 4.3 kg/m^2/day in second stage and 2 kg/m^2/day in first stage at a vacuum pressure of 0.5 bar. Indeed, the total productivity of the solar still is affected very much by changing the internal pressure. The productivity decreased as the pressure increased due to the lower evaporation rates at the higher pressure values.

Mahmoud et al. [61] experimentally investigated the performance of a multi stage water desalination still connected to a heat pipe evacuated tube solar collector. The results of tests demonstrate that the system produces about 9 kg of fresh water per day and has a solar collector efficiency of about 68%. They also suggests that for the evacuated tube solar collector with a 1.7 m^2 aperture the evaporation area in each stage should be 1 m^2, with the total number of stages equal to 4 or 5. With such rational design parameters the water productivity of the still could be considerably improved and reach the level of 11 kg/m^2/day.

6. Multi effect—Wick still

The daily yield of the inverted multi wick double effect solar still was 20% higher than the conventional multi effect still. The productivity increases with the decrease in flow rate for a particular length of still. Increasing the number of effect has a significant effect on the total yield of the still. The daily yield also increases with an increase of inlet water temperature, particularly in the second and third stage distillation [62]. Singh and Tiwari [63] inferred the performance of the double effect multi wick solar still (Fig. 15). Result shows overall thermal efficiency was decreases with increase in mass flow rate. In addition, thermal efficiency is always higher in the first effect than that of the second effect. Yeh and Chen [64] investigated the double effect wick still with airflow through second effect unit. In this work to improve the production rate water vapour carried out from the second effect unit. Considerable improvement in productivity was obtained when the airflow was conducted at the optimal rate, especially for lower strengths of insolation.

7. Multi effect—Diffusion still

Multiple effect diffusion type solar still has great potential because of high productivity and simplicity. In multi effect diffusion still, latent heat from condensation is recovered to cause further evaporation from the saline-soaked wick of second partition. In this manner evaporation and condensation process is repeated on all partitions in diffusion type still to increase the productivity. Elsayed [65] studied the parameters which affect the performance of the direct solar operated multiple effect diffusion still. The results of the modelling shows that the operational efficiency is improved by: (i) the increase

in the magnitude of the solar radiation flux, (ii) reducing the diffusion gap thickness, (iii) increasing the number of effects, (iv) reducing the feed rate to each effect, and/or using helium instead of air as diluent gas. The effect of changing the diffusion gap thickness, feed rate to each effect, and/or the kind of diluent gas on the operational efficiency of the still becomes more pronounced as the number of effects in the still is increased.

Tanaka et al. [66] investigated a parametric study of vertical multi effect diffusion still (VMED) with the heat pipe solar collector (Fig. 16). The still consists of a heat-pipe solar collector and a VMED still that consists of vertical and parallel partitions with narrow gaps between them. The partitions, except for the outside one, are in contact with saline-soaked wicks, and saline water is constantly feed to the wicks. The evaporation tubes attached to the under, surface of the collector plate of the solar collector and the condensing tube attached to the front surface of the first partition, are connected with two pipes so that a closed loop between the solar collector and the VMED still is formed. A constant mass of ethanol is charged into the closed loop, which is evacuated with a pump in order to be used as a heat-pipe. Solar radiation absorbed in the solar collector is transported to the VMED still by the heat-pipe as latent heat, and the solar energy is recycled in the VMED still to increase the production of distillate. The water in this still is feeding in upper part as shown in Fig. 16. The water vapour diffuses through a humid air layer between the partitions and condenses on the front surface of the next partition. Latent heat from condensation is recovered to cause further evaporation from the saline-soaked wick of second partition. Tanaka et al. [66] concluded as same as Elsayed [65] results. In addition to that the result shows that, the overall daily productivity is 9% or 17% larger for the optimum solar collector angle stills than the fixed one on the summer or winter solstices.

Total of 10 partitions with 5 mm or 3 mm diffusion gaps was predicted to produce 19.2 kg/m^2/day to 21.8 kg/m^2/day at a daily solar radiation of 24.4 MJ/m^2/day. The main advantage of this type still is, it can be folded or separated when it is carried, so that the still can be easy to carry and shipping cost would be very cheap [67].

Tanaka and Nakatake [68] theoretically investigated the VMED still with a flat plate mirror (Fig. 17). The still consists of 10 partitions with 10 mm diffusion gaps between partitions. It was predicted that it produce 29.2 kg/m^2/day and 34.5 kg/m^2/day on sunny spring equinox and winter solstice days, respectively at the equator. Tanaka and Nakatake [69] inferred the factors which reduces the productivity of VMED still with flat plate reflector. The result shows the productivity decrease in the increasing of diffusion gaps space between partitions. Also it was observed productivity decreases with increase in emissivity and decreases in reflectivity. It was visualized that, VMED still with flat plate collector can produce distillate more than 30 kg/m^2/day throughout the year at any latitude except for the winter season at 40°N latitude [70]. The daily productivity of VMED still with reflector, with 10 partitions was predicted to be about five or six times as large as that of a single-effect still [71,72].

8. Multi effect—Coupled still

In this type, basin still is coupled with the diffusion still to increase the productivity of the still. It has a basin still with a triangular cross-section consisting of a sloping double glass cover

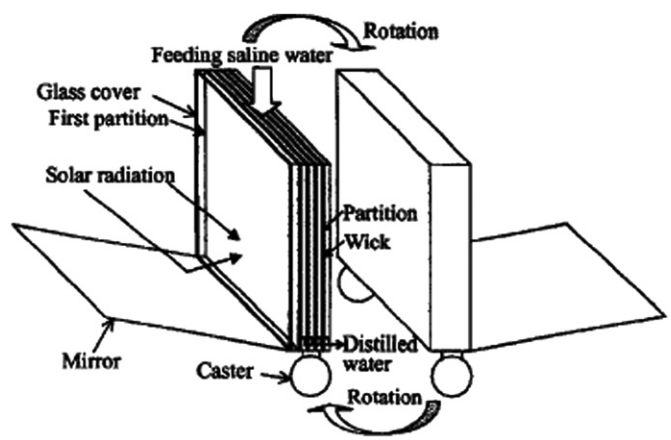

Fig. 17. Schematic diagram of a VMED still with flat plate mirror [68].

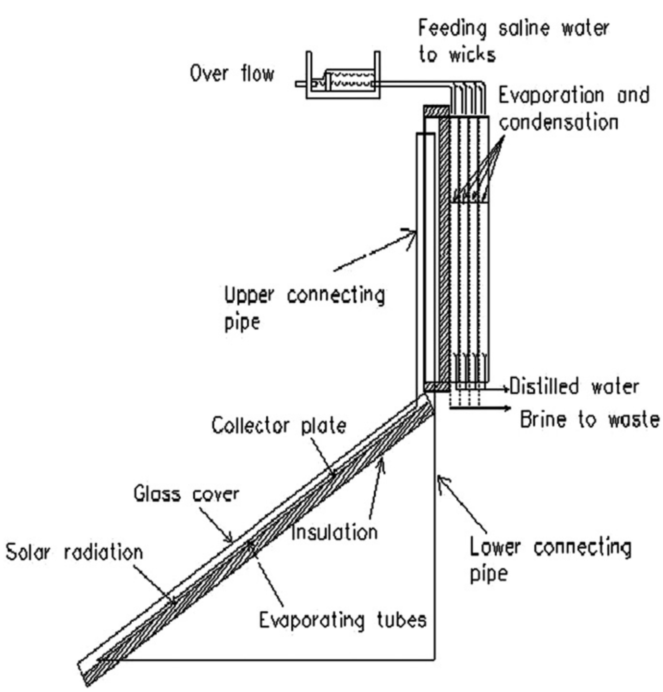

Fig. 16. VMED still with a heat pipe solar collector [66].

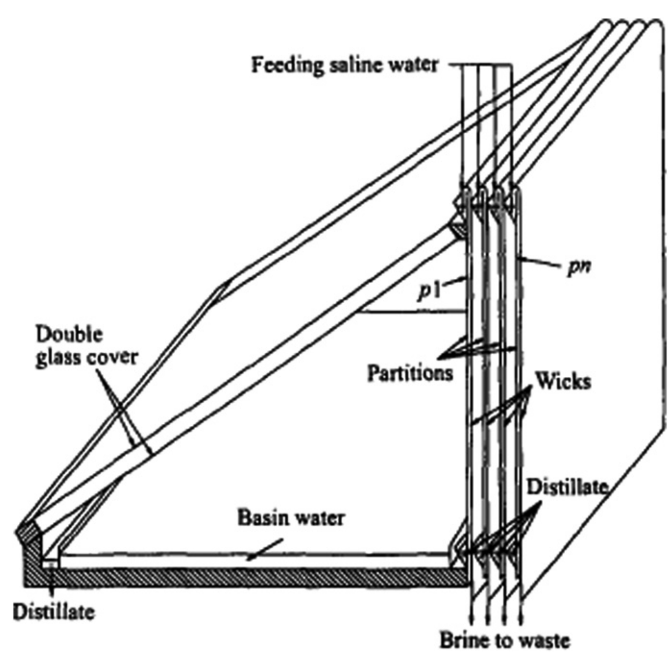

Fig. 18. Schematic of a basin-type, multiple-effect, diffusion-coupled solar still [75].

Table 1
Comparison of different stills for performance, economy, and maintenance.

S.No	Type	Performance	Economy	Maintenance	Remarks
1	Multi basin still	The productivity increased by 30% to 40% [11].	The investment is proportional with number of basin. Additional basin is almost made with transparent cover (glass).	Daily maintenance of additional basins is necessary. Because the salt will form as a layer in the basin and reduces the transparency.	Increasing the number of basins beyond three does not beyond this does not have significant effect on productivity [10]. It is due to reduced radiation entering into lower basins.
2	Multi basin still—double basin still, with different materials in the basin	Productivity enhanced by 169.2 when iron pieces were used in lower basin as energy storing material [31].	Additional basin increases the investment slightly. Compared to performance improvement, it is more economical.	The upper basin and material in the lower basin require regular cleaning.	Clean transparent saline water can only be used in upper basin.
3	Multi basin still—integrated with waste water flow	Productivity reaches around 9 kg/m^2/day with water temperature of 53 °C [36].	Additional investment is need for pumping the water.	Regular maintenance is need for avoid corrosion and salt deposition.	The wastewater is used for heat the brine feed water. Therefore the investment cost is low.
4	Multi basin still—integrated with flat plate collector (FPC)	Using of flat plate collector gives 50% higher yield than the normal double basin still [37].	Additional investment with flat plate collector and pumping system (if forced circulation).	There is chance for deposition of salt in the collector pipes due to saline water circulation. Regular cleaning of pipes is required.	For higher daily yield, the collector should be disconnected from the still during off sunshine hours.
5	Multi basin still—integrated with parabolic collector	Productivity normally reaches 14.684 kg/m^2/day [44].	Investment cost increases than FPC. Because design and fabrication is complex than FPC.	Regular cleaning of collector need to increase the reflectivity.	It needs some type of automatic tracking system to improve the productivity, rather than manual tracking.
6	Multi–stage and evacuated solar still	The productivity of the solar still can be up to 9 kg/m^2/day, and the distillation efficiency is 87% [60].	It increases the cost by means of vacuum pump, vapour trap and FPC.	Sealing should be checked regularly for airtight.	Based on this yield production of 3785.4 l/day, The collector's field area needed is estimated to be 600 m^2 plus a design factor of 20%. This gives a total collector area of 720 m^2.
7	Multi effect diffusion still—integrated with flat plate collector	It produces distillate more than 30 kg/m^2/day [69].	It requires higher investment than the basin and wick type solar still, also difficult in fabrication.	Replacing of wick is necessary. Regular cleaning of partition and partition gap is necessary.	The weak point of the diffusion type was found to be its operational and maintenance problems and the difficulty to be adapted to the field application.

facing the sun, a horizontal basin liner and a number of vertical partitions in contact with saline-soaked wicks. The vertical partitions may have small deformations, but any fibers protruding from the wicks absorb saline water, become heavier and are gradually suppressed by gravity. This makes it possible to reduce the gaps between partitions to 10 mm or less, which increases productivity significantly. Coupled still of 10 vertical cells with 5-mm gaps is theoretically predicted to produce 15.4 kg/m^2/day on a sunny day of daily solar radiation of 22.4 MJ/m^2/day on the glass cover, and its cumulative efficiency is about 3.5 times greater than the average experimental value of the conventional basin-type stills [73]. Tanaka et al. [74] investigated the parameters affects the coupled still performance in summer and winter condition. The result of the analysis was summarized as: (i) Productivity was greater in autumn than in spring because of the higher ambient air temperature in autumn. (ii) Exponential increases in productivity with number of cells, but with fewer cells it shows a drastic increase. (iii) Productivity as well as the peak temperature of the basin gradually decreases with an increase in the initial saline water mass in the basin. (iv) The basin-type multiple-effect coupled still is about four times more productive than basin type stills, and more productive than the conventional multiple-effect stills by about 40% or more. The productivity of the coupled still was increased by narrowing the diffusion gaps from 10 mm to 5 mm, but the productivity with 5-mm gaps is smaller than the prediction by approximately 40% (Fig. 18) [75].

9. Conclusions

Table 1 summarizes the performance, economy of the still and operational and maintenance aspects of different types of multi effect solar stills. On the basis of above discussion in various sections, the following conclusions can be inferred:

- It is suggested to use the multi effect solar still instead of single-effect still, which leads to increased productivity by utilization of latent heat energy and cost saving.
- The yield is increased by flowing of water over the upper glass of the multi basin still.
- The evaporative heat-transfer coefficients are strong functions of temperature, whereas the convective and radiative heat-transfer coefficients vary little with temperature.
- Supplying of waste hot water in basin increases the basin water temperature and leads to increase the evaporation rate.
- Inverted absorber stills are reduces the bottom heat loss and approximately increases the productivity by double.
- Integrating of flat plate collector in solar still increases the productivity by huge. Forced circulation mode gives higher yield than that of the thermosiphon mode. But, thermosiphon mode is more useful for high-temperature distillation, especially at a location where electrical power is not available.
- The flat plate collector should be disconnected during off sunshine hours to reduce the heat loss through collector.
- The yield of the still is directly proportional to flat plate collector area.
- Using of parabolic collectors increases the yield more than flat plate collector. But it needs some kind of tracking system.
- Multi effect wick stills are produced more the yield than basin still during sunshine hour, and reverse in the case of night.
- Providing additional area for condensation increases the condensation rate as well increases the evaporation rate in basin.

- Multistage, stacked tray solar still produces more distillate than that produced by the ordinary solar still.
- Multi effect diffusion still with flat plate collector and reflector gives better result than ordinary solar still.

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